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Laser integration on silicon photonic circuits through transfer printing

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Laser integration on silicon photonic circuits through transfer printing

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Summary

In this project we develop a transfer printing process for the massively parallel integration of III-V lasers on silicon photonic integrated circuits. We discuss the technological process that has been developed as well as the results of the very first III-V-on-silicon transfer printed single wavelength laser.

Introduction

Silicon has long offered promise as the ultimate platform for realizing compact photonic integrated circuits (PICs). That promise stems in part from the material's properties: the high refractive-index contrast of silicon allows strong confinement of the optical field, increasing light-matter interaction in a compact space—a particularly important attribute for realizing efficient modulators and high-speed detectors. Even more important, however, silicon photonics relies on materials and processing techniques already highly developed by the silicon CMOS industry. This means it can leverage the best tools and processes available, without the need for high additional capital investments, raising the potential for high performance at low cost.

Thus far, applications in telecom and data communications have driven most industrial development in silicon photonics, though research is also under way in biosensing, spectroscopy and more exotic domains such as quantum optics and optomechanics. Silicon-based PICs have become widely available both for large industrial firms, through several commercial wafer foundries, and for small- and medium-sized enterprises (SMEs) and universities, through multiproject wafer services such as Europractice and IME. The AIM Photonics project in the United States also promises new development in the techniques and technology for silicon photonics.

Yet amid all of that progress, the field has faced a big stumbling block: the lack of an integrated laser source. Thus far, silicon-photonics applications have had to rely on external laser sources that feed the optical chip through optical fiber, or on flip-chip integration of separately fabricated laser diodes. Neither of those approaches is scalable to very large wafer volumes or to more complex laser designs. Over the last few years, however, the research community has made tremendous strides toward realizing fully integrated laser diodes on silicon, both through wafer-bonding techniques that integrate direct-bandgap III-V epitaxial materials into prefabricated silicon circuits, and through direct epitaxy of III-V semiconductors on silicon.

In this project the aim is to develop a new approach that combines best of both worlds: the integration of high quality III-V epitaxial material (an attribute of wafer bonding) and the possibility to only very locally deposit III-V material on a photonic integrated circuit (an attribute of direct epitaxy). This approach is coined transfer printing.

Methods, Assumptions, and Procedures

Wafer bonding, while an established integration method, can lead to inefficient use of the III-V material, and can make co-integration of different III-V semiconductor layer stacks difficult. The Photonics Research Group is developing a new process that tackles these issues. The process rests on transfer printing of micrometer-size semiconductor chips, or coupons, from a III-V source wafer to a silicon photonic target wafer using an automated tool. The result could be very efficient use of the III-V source material, low-cost wafer-scale integration of such coupons and dense co-integration of different III-V materials. The method is illustrated in Figure 1. The process starts with a III-V source wafer that carries a sacrificial layer (InGaAs) and a III-V device layer. The III-V wafer is patterned into a dense array of coupons as shown in Fig. 1(b) after which the coupons are covered with a polymer tether structure. This structure has openings in order to selectively etch away the sacrificial layer, such that the III-V device layer is released from the growth substrate. Using a patterned PDMS stamp such coupons can then be picked up (Fig. 1e) and printed (Fig. 1f) to a silicon photonic target wafer. While this process can be done one coupon at a time, the true value of the transfer printing approach is that it allows the massively parallel transfer of III-V coupons to a silicon photonic target wafer. Using multiple and different source wafers different III-V epitaxial layer structures can be intimately integrated.

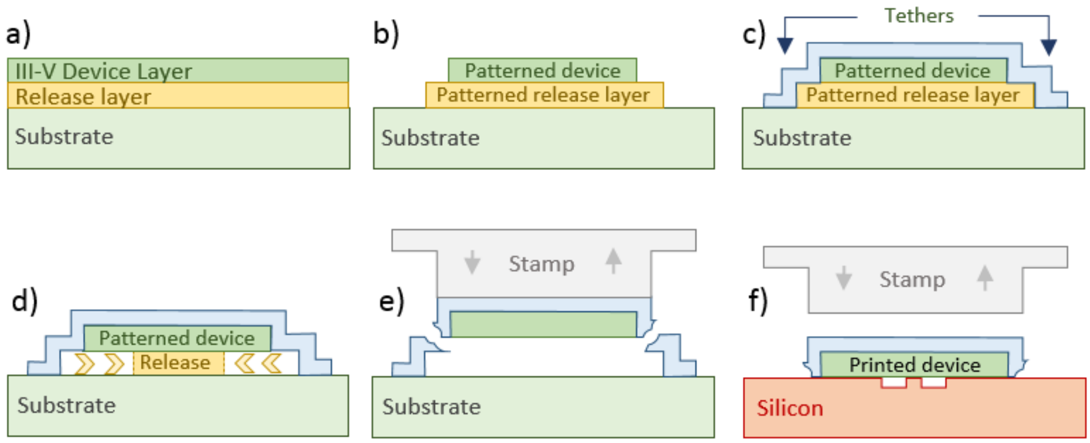

Figure 1: transfer printing process flow

Results and discussion

In this project we developed the transfer printing of InP-based epitaxial layer structures onto a silicon photonic integrated circuit, to realize a III-V-on-silicon single wavelength laser. Devices were successfully realized and their static and dynamic characteristics were assessed.

A critical step in the transfer printing process is the release of the sacrificial layer InGaAs layer with good selectivity with respect to the InP cladding layers. A table with the solutions that were evaluated is given below.

Table 1. Chemicals tested for undercutting and the observed etching behavior.

Etchant	Observations
H_2SO_4:H_2O_2:H_2O (1:1:18)	Partial undercutting
H_3PO_4:H_2O_2:H_2O (1:1:20)	Partial undercutting
Chromium etchant	Partial undercutting
HF:H_2O_2:H_2O (1:1:10)	Full undercutting Poor selectivity Encapsulation delaminates
Citric acid : H_2O_2 (1:10)	Full undercutting Slow etching speed Anchors delaminate
Tartaric acid : H_2O_2 (1:1)	Full undercutting Selectivity to InP >500
$FeCl_3$:H_2O (3 mol/l) @ RT	Full undercutting Selectivity to InP >500
$FeCl_3$:H_2O (3 mol/l) @ 5°C	Full undercutting Selectivity to InP >2000

The first three options failed to undercut the complete structure of 40um wide. This is because of anisotropic etching, where a slow etching crystal plane is being exposed when the coupons are aligned along the crystal axes. The HF-based and citric-acid-based etch mixtures rendered a full undercut, but attacked the photoresist based anchors and encapsulation layer. While this could be resolved by using other encapsulation layers, because of the poor selectivity and slow etching speed respectively, these etching solutions were discarded as well. Excellent results were obtained with the $FeCl_3$:H_2O solution at 5°C. Using this etchant it takes 2 hours to undercut the 40um wide coupons, with only an InP thickness variation of 20 nm.

After developing the III-V transfer printing process, Si photonic integrated circuits comprising silicon gratings and spot-size converters were designed and fabricated to realize a III-V-on-silicon distributed feedback laser that is coupled to the silicon waveguide layer. A schematic view of such a device is shown in Fig. 2. In this case the III-V material is transfer printed onto the planarized silicon waveguide circuit after which the III-V coupon is processed, lithographically aligned to the underlying SOI waveguide circuit. A 50nm DVS-BCB layer is used as an adhesive bonding layer. Figure 3 shows a microscope image of an array of III-V-on-silicon DFB lasers after transfer printing and III-V processing.

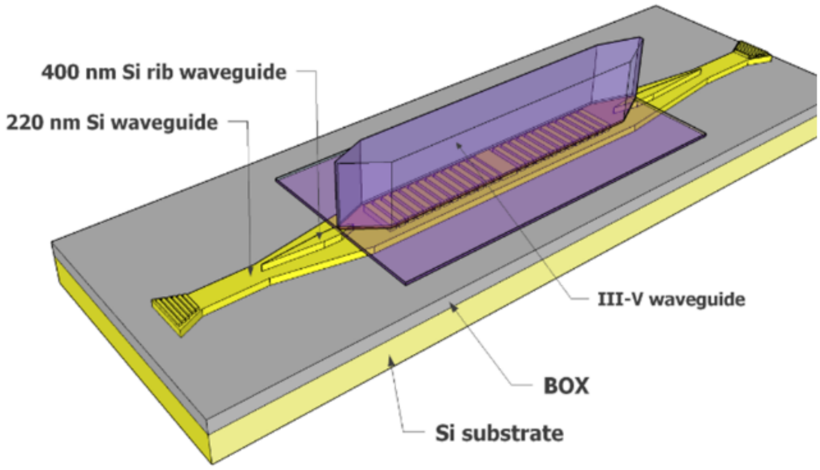

Figure 2: schematic of a transfer printed III-V-on-silicon distributed feedback laser

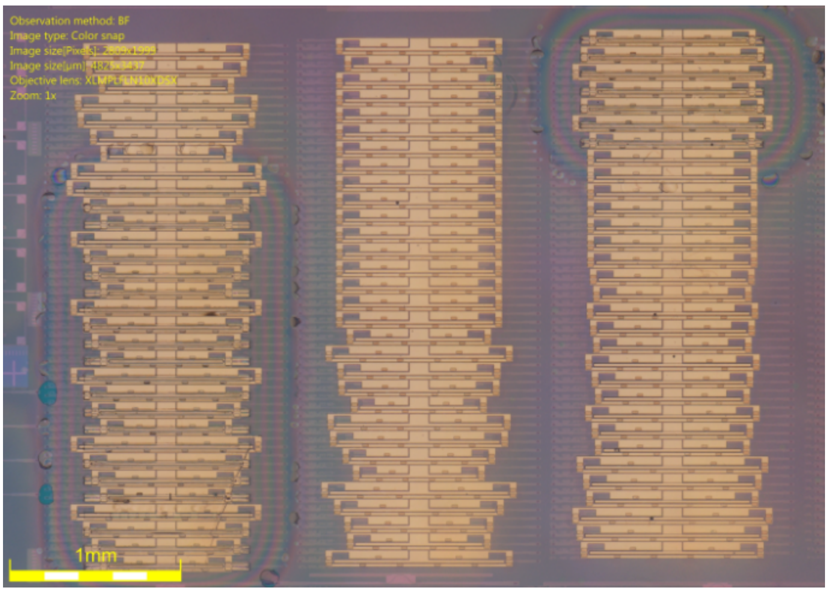

Figure 3: array of transfer printed III-V-on-silicon DFB lasers

Both static and dynamic characterizations were carried out for such devices. A typical light versus current plot is shown in Fig. 4 (left). While the output power of the laser coupled to the silicon waveguide is relatively high, mode hops can be observed. These are attributed to parasitic external reflections due to imperfect processing conditions. Efforts are currently being made to improve the device processing. Next to the static characterizations we also performed small-signal dynamic characterization. A typical result is shown in Fig. 4(right), showing a small-signal bandwidth above 10GHz, making this an interesting source both for digital optical communication and radio-over-fiber transceivers.

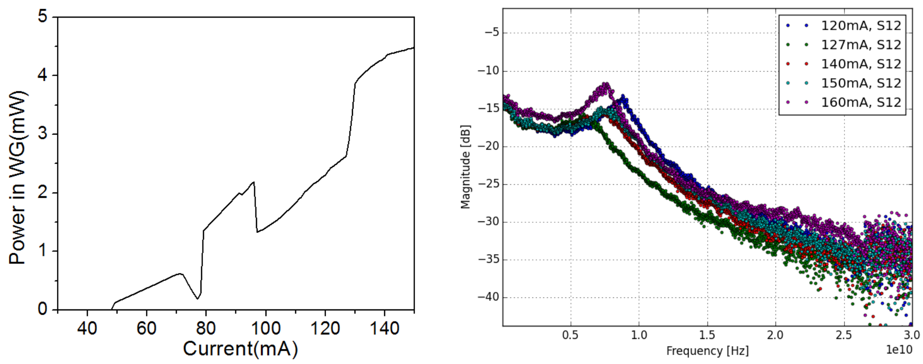

Figure 4: (left) light-versus-current curve of the III-V-on-silicon DFB laser; (right) small signal characterization of this laser.

Conclusions

We successfully realized for the first time the transfer print integration of a III-V-on-silicon laser coupled to a silicon waveguide circuit. While process improvements are still possible, this demonstration showcases the great potential of transfer printing technology for the wafer-scale integration of III-V laser sources.

References

List of Symbols, Abbreviations and Acronyms

PIC Photonic Integrated Circuit
CMOS Complementary Metal Oxide Semiconductor
SME small- and medium-sized enterprises
DFB distributed feedback laser